Conf-920819--2

SAND--92-1820C

DE93 000754

IAF-92-0568
SYSTEM MODEL DEVELOPMENT FOR NUCLEAR THERMAL PROPULSION

James T. Walton
NASA Lewis Research Center

Nelson A. Hannan
Argonne National Laboratory

Ken R. Perkins
Brookhaven National Laboratory

John J. Buksa
Los Alamos National Laboratory

Brian A. Worley
Oak Ridge National Laboratory

Dean Dobranich
Sandia National Laboratories

43rd CONGRESS OF THE INTERNATIONAL ASTRONAUTICAL FEDERATION
August 28-September 5, 1992/Washington, DC

SYSTEM MODEL DEVELOPMENT FOR NUCLEAR THERMAL PROPULSION

James T. Walton
NASA Lewis Research Center
Cleveland, Ohio USA

Nelson A. Hannan
Argonne National Laboratory
Argonne, Illinois USA

Ken R. Perkins
Brookhaven National Laboratory
Upton, New York USA

John J. Buksa
Los Alamos National Laboratories
Los Alamos, New Mexico USA

Brian A. Worley
Oak Ridge National Laboratory
Oak Ridge, Tennessee USA

Dean Dobranich
Sandia National Laboratories
Albuquerque, New Mexico USA

ABSTRACT

A critical enabling technology in the evolutionary development of nuclear thermal propulsion (NTP) is the ability to predict the system performance under a variety of operating conditions. This is crucial for mission analysis and for control subsystem testing as well as for the modeling of various failure modes. Performance must be accurately predicted during steady-state and transient operation, including startup, shutdown and post operation cooling. The development and application of verified and validated system models has the potential to reduce the design, testing, cost and time required for the technology to reach flight-ready status.

Since October 1991, the U.S. Department of Energy (DOE), Department of Defense (DOD) and NASA have initiated critical technology development efforts for NTP systems to be used on Space Exploration Initiative (SEI) missions to the Moon and Mars. This paper presents the strategy and progress of an interagency NASA/DOE/DOD team for NTP system modeling. It is the intent of the interagency team to develop several levels of computer programs to simulate various NTP systems. The first level will provide rapid, parameterized calculations of overall system performance. Succeeding computer programs will provide analysis of each component in sufficient detail to guide the design teams and experimental efforts. The computer programs will allow simulation of the entire system to allow prediction of the integrated performance. An interagency team was formed for this task to use the best capabilities available and to assure appropriate peer review.

The vision and strategy of the interagency team for developing NTP system models will be discussed in this paper. A review of the progress on the Level 1 interagency model is also presented.

BACKGROUND

During the summer of 1989, President Bush presented a National vision focused on returning man to the Moon and then travelling on to Mars. This was the commencement of NASA's Space Exploration Initiative (SEI). Since that time, a variety of studies and commissions have reasserted the desirability of an NTP system for interplanetary propulsion to fulfill the Space Exploration Initiative (ref. 1, 2, 3). In addition to reducing the gross launch mass by up to 50 percent and decreasing launch costs, in comparison to chemical systems, nuclear thermal propulsion offers enhanced astronaut safety by lowering the inter-galactic cosmic radiation dose to the crew through reduced mission transit time.

Nuclear thermal propulsion systems operate by using propellant to cool a nuclear reactor core, yielding a high-temperature gas for expansion through a nozzle. The reactor core replaces the combustion process of bipropellant chemical propulsion systems as the source of heat. Because only a single propellant, such as hydrogen with its low molecular weight, is required for NTP, the system can achieve more than twice the thrust efficiency of chemical propulsion. A schematic of a generic NTP system is shown in Figure 1.

The current NTP concept definition and technology development efforts are founded on a strong historical data base. Beginning in the mid-1950's, the United States government and private industry have sponsored research and development activities aimed at producing nuclear rockets, ramjets, and turbojets (ref 4, 5, 6) through an investment of nearly $10B (1992). The pinnacle of this legacy was the reactor and engine tests of the NERVA program which culminated in 1973 with a "flight-ready" design. Because the NTP system integrates a nuclear reactor with chemical rocket technology, NASA and DOE have been working cooperatively on its concept definition and technology development.

The concept definition and systems engineering activities involve the development of an NTP configuration which meets astronaut safety, SEI mission requirements, and NTP stage requirements. The primary variable in the system configuration is the nuclear reactor fuel form for which; candidate forms include prismatic, particle, and wire (Figure 2). The technology development activities involve the investigation of (1) high-temperature, long-life (hours) fuels, (2) low mass, high-performance nozzles, (3) high-efficiency, low mass turbopumps, and (4) reliable, autonomous system controls and health management systems.

A critical task in these activities is developing the ability to predict system performance under a variety of operating conditions. The capacity to model system performance is required for concept definition activities to evaluate each configuration on a common basis. This capability also aids the technology development activities by providing a means to evaluate the benefits to the system from component improvements and by providing a diagnostic tool for understanding experiments. Moreover, the ability to predict the system performance is critical for mission analysis and for control subsystem testing, as well as for the modeling of various failure modes. Performance must be accurately predicted during steady-state and transient operation, including startup, shutdown and post operation cooling. System models will access component models for the reactor, nozzle, turbopumps, and lines with a propellant properties model. The development and application of verified and validated system models has the potential to reduce the testing, cost and time required for new advanced NTP systems to regain flight-ready status.

An integrated NASA-DOE team was formed in late 1991 to develop and implement a strategy for modeling NTP systems that conform to the schedule for concept definition and technology development activities. An interagency team was formed to integrate the best capabilities available and to assure appropriate peer review. The team members include personnel from the following DOE laboratories: Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Idaho National Engineering Laboratory (INEL), Los Alamos National Laboratory (LANL), Oak Ridge National Laboratory (ORNL), and Sandia National Laboratories (SNL); and personnel from the NASA Lewis Research Center (LeRC) and the Marshall Space Flight Center (MSFC). The team also includes personnel from the DOD Phillips Laboratory to facilitate the interchange of technology developed under the NASA SEI NTP program and the DOD Space Nuclear Thermal Propulsion (SNTP) program.

The interagency NTP system modeling team convened four times between December 1991 and August 1992 at LeRC, SNL, BNL and MSFC, respectively. The purpose of these meetings was to develop an overall modeling vision and to implement near-term strategies for its realization. It is the intent of the interagency team to develop several levels of computer programs to simulate NTP system performance based on various fuel forms. The first level will provide rapid, parameterized calculations of overall system performance. Succeeding computer programs will provide analysis of each component in sufficient detail to guide the design teams and experimental efforts. Note, these system models are not intended to replace requisite individual component analysis of the reactor, turbopump or nozzle. The following sections outline the vision and the near-term strategies developed by the interagency NTP system modeling team.

INTERAGENCY TEAM MISSION

The purpose of the interagency modeling team is to integrate state-of-the-art computational resources and techniques, with the current knowledge base, to produce simulations of NTP system performance. The end products will provide users with a variety of validated and/or verified system models to assist in designing and to reduce the testing, cost, and time to reach a flight ready status. This vision can be best achieved by a NASA/DOE/DOD team which can use the unique capabilities of each team member and assure joint support for the resulting models.

TEAM OBJECTIVE

A computer model of NTP systems is required for several reasons. First, a parametric NTP model can to predict system performance for several engine configurations on a consistent basis. In other words, a common tool is required to compare the configurations on level grounds; performance numbers for each configuration exist from a variety of sources. Second, a parametric NTP model is required to generate configuration performance data for input into mission analysis codes. Third, a parametric model is required to provide state-point input conditions to the system component designers and analysts. Fourth, an NTP system model is needed to evaluate the effect on performance of system design perturbations (i.e., sensitivity studies). Fifth, an advanced model can evaluate the performance of a given system through startup and shutdown transients. Sixth, a detailed transient model of the experimental engine is required for linkage to the facility model to determine engine-facility interactions. Last, an advanced NTP model can be connected to a control system in order to exercise the control system prior to its integration with hardware. To realize the vision and meet the needs defined above, the objective of the interagency team will be to develop five distinct computer programs, each varying in the level of detail and capability, to simulate NTP system performance.

Level 1 Model

The Level 1 model is envisioned to be a relatively simple parametric system model. The primary focus of this program will be to analyze the performance of a variety of configurations, including NERVA-derivative, particle-bed, and CERMET reactor-based NTP systems. This program is expected to analyze steady-state performance and to require a run time on the order of minutes. The secondary focus of this program will be system design. The target user market for this program includes mission analysis groups, component modeling groups, and concept evaluation teams. The Level 1 model is comparable in the level of detail to the Nuclear Engine System Simulation Program, NESS, (ref. 7) developed under NASA contract NAS3-25809. Program NESS is an NTP system design tool that combines a NERVA-derivative reactor model, ENABLER, developed by Westinghouse Electric Corporation with the Expanded Liquid Engine Simulation Program, ELES, developed by Aerojet General Corporation. NESS determines a system configuration given its performance.

Level 2 Model

The Level 2 model is envisioned to be a near-term, detailed, transient system analysis program. It may use an existing base architecture program and will be capable of modeling system startup and shutdown as well as system feedbacks and oscillations. Since this level of analysis will involve multidimensional reactor neutronic solutions, this program will be used once reactor designs are reasonably fixed. The program should be capable of handling control drum rotations, turbopump assembly (TPA) startup, stress analysis, decay heating, and detailed nozzle heat transfer analysis accounting for neutron/gamma heating. It is anticipated that this program will not have neutronic criticality and power density analysis integrated into the base architecture although reactor dynamics will be included. The target user market for this program includes component modeling groups and concept evaluation teams. The Level 2 model will also be used parametrically by the interagency team to identify modeling requirements for the Level 3 model.

Level 3 Model

The Level 3 model is envisioned to be a far-term, detailed, transient system analysis program. This integrated performance analysis program will be based on state-of-the-art methodology at the time of the base architecture program development. The component models must be verified by older component models and/or validated by component experimental data. This program will provide information similar to that of the Level 2 model. It is anticipated that this program will have neutronic criticality and power density analysis integrated into the base architecture or will provide a means for easy information transfer through coupling. The target user market for this program includes component modeling groups and concept evaluation teams. This model will include two-phase and multi-dimensional flow capability. The model will also include shock-capturing numerics to allow simulation of severe accident conditions.

Level 4 Model

The Level 4 model is envisioned to be a modified version of the Level 3 program tuned to model the experimental or flight engine. The target user market for this program includes component modeling groups, control system developers, and engine performance analysts. The Level 4 model is a 1990's version of the Nuclear Engine Transient Analysis Program, NETAP, (ref. 8, 9) of the NERVA project from the view point that this program was tailored for a specific configuration. The NETAP Program is a finite-difference, explicit-solution, digital computer program that calculates the material temperature and the propellant temperature and pressure distributions as a function of time throughout the NERVA engine system.

Level 5 Model

The Level 5 model is envisioned to be a real-time, transient simulation model of the experimental or flight engine. The target user market for this program includes engine operator training groups and flight engine performance review teams. This model is similar to the Common Analog Model, CAM, (ref. 10, 11) of the NERVA project. The CAM was developed to describe the dynamic behavior of the NERVA 400E engine configuration by using correlations and curvefits of actual component physics.

The performance of the interagency team will be measured first by its ability to provide the models to the users at the appropriate time according to the schedule of concept definition and technology development activities. The current schedule is shown in Figure 3. Second, the team performance will also be measured according to the accuracy and reliability of each model's output. This performance measure relies on the availability of experimental data for bench marking and on sufficient peer review of the models' algorithms; the standards for each model, explicit in each models' software design requirements document, have yet to be defined. Third, the team performance will be measured according to the useability of each model; in other words, the degree of user friendliness and the length of run time. These are subjective performance measures which require feedback from the users.

STRATEGY DEVELOPMENT & IMPLEMENTATION

The strategy for developing each system model is similar and is divided into subtasks as shown in Table 1. The strategy begins with the identification of the users needs by compiling the Software Design Requirements Document and with the identification of the program structure. Subsequent tasks merely reflect the means to assemble the structure and meet the requirements; therefore, the subsequent tasks evolve from the selected program structure.

To date, activities have focused on the Level 1 system model. The following sections outline those activities and the near-term milestones.

Level 1 Strategy

Task 1.- The first component of the Level 1 strategy was the development of a software design requirements document. This document was developed by the interagency team with input from several users. Table 2 presents the overall program requirements. This task was completed in March 1992, although the requirements document will evolve over time.

Task 2.- To meet the requirements, the overall program structure shown in Figure 4 was identified in March 1992. To best satisfy the requirements, the team decided to use a general, finite-element, fluid system analysis program as the base computational engine. The input file to such a program contains all the configuration-specific information. Therefore, because the input file will be lengthy, an input preprocessor will be created to interface with the user. The preprocessor will prompt the user for information, such as reactor type and system thrust level, and it will generate the appropriate input file, specifying dimensions, material properties, and reactor power profiles. The preprocessor will access material property and reactor physics data bases to retrieve appropriate data for inclusion in the input file.

The one-dimensional, finite-element system analysis program incorporates the ability to model pump, turbine, and nozzle performance in such a way as to provide true integrated performance. In addition, the program includes a propellant thermodynamic and transport properties model This overall approach was used so that the component models could be developed separate from the common com tional engine. With this approach, the overa.. effort can be distributed and a change to one model will not impact the development of another.

Task 3.- Next, the Level 1 strategy called for the evaluation and selection of a base computational engine. After a review of the available programs in light of the Level 1 requirements, the team identified only one program with the potential to be the base computational engine: the SAFSIM program (ref. 12). This program is currently slated to be used within the Level 1 system model.

Any one-dimensional, finite-element program must rely on correlations for friction factors and heat transfer coefficients to predict pressure drop and wall temperatures through a fluid control volume. One of the key constituents to be modeled is the fuel element. To assist the interagency team in the evaluation of the various heat transfer coefficient and friction factor correlations, a computer program was developed to compare the correlations for hydrogen flow through a tube with internal heat generation. The program, ELM (ref. 13), has been used to compare the available correlations on a consistent basis and to compare temperature distributions with the previous nuclear rocket fuel element experimental data.

Task 4.- The purpose of the fourth strategic element was to develop a reactor physics data base to be linked with the preprocessor. The inputs to the data base from the program includes the following: (1) reactor type, (2) power level and hydrogen flow rate, (3) operating history, and (4) internal shield thickness. The output from the data base to the program falls in two categories, internal and external reactor physics. The internal output consists of axial and radial heating rates for the fuel elements, support elements, moderator, reflector, and internal shield, along with the effective neutron multiplication factor (k_{eff}). The external output consists of radiation dose rates at a variety of locations that may include the following: (1) nozzle wall, (2) turbopump, (3) external shield, (4) tank, and (5) habitation module.

A method for modeling the reactor physics of the three reactor configurations was agreed upon. First, the cross-section data base to be used for all analyses will be ENDF/B-V with the ORNL graphite modifications. Second, the NJOY Program (ref. 14) will be used to access ENDF/B-V when cross-section data is required at different temperatures. Third, the MCNP Program (ref. 15), Version 4.2, will be used to analyze the three geometries and to provide the necessary output. Note, at the present time, MCNP contains a cross-section data base from ENDF/B-V which was generated at 300 K. Because the temperatures in the reactors will vary from 100 to 3000 K, it will be necessary to extract additional cross-section data in the near future. This Monte Carlo method transport analysis will be supported with calculations from diffusion theory and discrete-ordinate transport codes.

The first entries to the reactor physics data base will be steady-state internal physics data for each reactor configuration at three power levels using the 300 K cross sections.

Task 5.- The fifth task of the Level 1 model strategy was to develop pump, turbine, and nozzle, performance models. These models will interface with the base finite-element program as will the propellant properties model. For Level 1, pump and turbine performance will be modeled using characteristic maps. The characteristic maps (Figure 5) will be provided by experimental data for existing turbopumps and by TPA performance codes for modified hardware. Nozzle performance will be modeled by tables of specific impulse generated by the Two Dimensional Kinetics Program, TDK, (ref. 16) using the boundary layer correction scheme. The specific impulse tables will be generated for various chamber pressures and temperatures, area ratios, and wall cooling levels.

As mentioned in the previous paragraph, a standardized propellant properties model is required to interface with the base computational engine. The propellant of choice for SEI missions is hydrogen. Nominally, hydrogen is a mixture of orthohydrogen and parahydrogen, which differ by the direction of the nuclear spin of the atoms within the molecule. The mixture compositions vary from 100 percent parahydrogen near liquid temperature to 25 percent near room temperature and above; without a catalyst, the rate of conversion from parahydrogen to orthohydrogen at a temperature variation is on the order of days.

As a propellant for NTP systems, hydrogen is exposed to significant radiation fields. Experiments conducted during reactor tests in 1968 indicated that intense radiation fields hasten the conversion from parahydrogen to orthohydrogen (ref. 17). Because the properties of parahydrogen and orthohydrogen are significantly different between 56 and 390 K, the extent of conversion within the nozzle and reflector would be important to their thermal design and nuclear analysis. The historical data indicate that in the range of power levels of interest, the orthohydrogen content is below 15 percent; therefore, it would be a reasonable assumption to approximate the propellant as 100 percent parahydrogen.

A computer program for the interagency modeling effort was recently developed to provide selected parahydrogen thermal and transport properties which match the National Bureau of Standards parahydrogen data (ref. 18). The program, NBS+-pH_2 (ref. 19), was created by computerizing the required NBS parahydrogen data (density, thermal conductivity, viscosity, Prandtl number, entropy, enthalpy, specific heats, and speed of sound) and by using table lookups with linear interpolation to cover a wide range of pressures (0.01 to 16 MPa) and temperatures (20° to 10000°K).

Task 6.- When the preliminary versions of the component models are available, they will be integrated with the preprocessor and the base computational engine. The development of the baseline input files for each configuration is critical to the preprocessor development.

Task 7.- Following the system model integration will be a checkout and validation phase. During this phase, the model will be verified by the NETAP program and validated against NRX-A4/EST and XE-1 experimental data (ref. 20, 21). Model inaccuracies and weaknesses will be identified and documented.

Task 8.- To provide for the widest dissemination and utilization, the Level 1 model will be fully documented after it is checked and validated. A detailed users manual will include the model methodology, governing equations and implementation, numerical methods, logic flow diagrams, and subroutine descriptions. Included in the manual will be sample input and output listings for each reactor configuration

Task 9.- To reduce the learning curve for the Level 1 model, a graphical user interface will be developed. This interface will provide a window-oriented environment in which the user can design the NTP configuration, create the input file, run the program, and view the output. Because of the nature of the graphical interfaces, it is likely that this will be machine-specific coding.

FUTURE DIRECTION

The accurate prediction of transient performance is critical to system design and testing, as well as to mission design and analysis. The system must start up and shut down in a controllable manner without extreme pressure and temperature gradients or oscillations. Moreover, once shutdown, low propellant flow rates will be used to remove fission-product-decay heat affecting the mission specific impulse. After Level 1, all subsequent models will have transient analysis capability. The Level 2 model will use existing models whereas the Level 3 model is anticipated to leverage current and new code development efforts.

Once reactor configurations are more clearly defined and the team's focus shifts to higher level models, a number of reactor physics codes and methodologies will be employed to assure a robust analysis. Monte Carlo methods will be used in conjunction with diffusion theory and discrete-ordinate transport codes. More detailed axial and radial power distributions and reactivity margins will be calculated as a function of operating history (burnup) and control drum position. Significant effort will be spent in determining all reactivity feedback coefficients for use in transient analyses. The problem of deep penetration of radiation associated with modeling complete spacecraft radiation fields (including reactor and non-reactor sources) is a very challenging problem. Use of a coupled Monte Carlo/discrete-ordinate methodology, as opposed to only separate methods, may be an optimal approach.

The interagency team has begun preliminary planning for the Level 3 model. Because this generic model is envisioned as a state-of-the-art, multidimensional, transient system analysis model, the long lead time necessitates early planning. It is expected that this model will be applied to reasonably fixed-system configurations and will leverage new computational technology (Fortran/90, Object Oriented Programming, Parallel Processing) to achieve run times on the order of a few hours for a startup or shutdown analysis case. Several configuration options have been identified for the Level 3 model: the first is to link an existing Monte Carlo reactor code with a transient fluid mechanics (F-M) code, such that the steady-state reactor code is called stepwise with time by the fluid mechanics code; a second is to develop a transient three-dimensional reactor dynamics code and interfacing it with a transient fluid mechanics code; the third, and most difficult, option is to develop a coupled reactor physics and fluid mechanics code. The team concluded that, prior to proceeding with a particular option, experience with the Level 2 model and existing one-dimensional transient models should be gained and that experimental validation of existing neutronics models should be completed for these fuel forms.

CONCLUDING REMARKS

An interagency NASA/DOE/DOD effort was initiated to develop several models for predicting the performance of nuclear thermal propulsion systems. These models are being developed to support the evaluation of conceptual designs and to provide a diagnostic tool for understanding system tests. Once verified and validated, these system models will aid in regaining the flight-ready status of nuclear thermal propulsion vehicles faster, cheaper, better and more safely by verifying design configurations and minimizing full-scale ground tests.

ACKNOWLEDGEMENT

The authors would like to acknowledge the contributions of other participants of the interagency nuclear thermal propulsion system modeling team who have gone beyond the call of duty to provide technical insight and to cultivate management support for this activity. Additional team members, who deserve recognition, include: Mr. Warren Madsen (INEL), Mr. Tony Zuppero (INEL), Mr. Bill Rider (LANL), Mr. R.T. Perry (LANL), Mr. Felix Difilippo (ORNL), Ms. Margaret Proctor (LeRC), Mr. Terry Hardy (LeRC), Mr. Harold Gerrish (MSFC), and Mr. Ken Hampsten (PL).

	TARGET DATE				
STRATEGY	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
Compile Software Design Requirements Document	03/92	09/92	10/92	06/96	06/96
Identify Program Structure	03/92	09/92	11/92	n/a	08/96
Select Base Architecture	07/92	10/92	n/a	n/a	09/96
Develop Reactor Physics Model	08/92	12/92	01/95	n/a	10/98[2]
Develop Reactor F-M Model	n/a	n/a	01/95	n/a	10/98[2]
Develop Turbopump Assembly & Nozzle Performance Model	08/92	12/92	01/95	n/a	10/98[2]
Integrate Component Models with Preprocessor	09/92	01/93	06/95	n/a	12/98
Verify & Validate Model	09/92	04/93	09/95	07/97[1]	12/98
Document System Model	12/92	06/93	12/95	12/98	04/99
Develop & Integrate User Graphical Interface	04/93	04/93	01/96	n/a	04/99

[1] calibrate with experimental data [2] simplified correlations

Table 1 - Nuclear Thermal Propulsion System Modeling Strategy

Programming Language:	Fortran/77 (no extensions)
Computer System:	Machine independent
Operating System:	Operating system independent
Operating Mode:	User-interactive/user-friendly
Nominal Runtime:	3 min. for single pt. solution on a 80386-25
Propellant Properties:	Para-hydrogen (NBS Monograph 168, 1981)
Minimum Solution Type:	Steady-state performance analysis
Verification:	Verify operation against more detailed models
Validation:	Validate with experimental data
Documentation:	Detailed User's Manual including methodology, flow diagrams, subroutine descriptions, and sample test case input and output
Dissemination:	Available for release through the National Energy Software Center and COSMIC

Table 2 - Level 1 Model Requirements

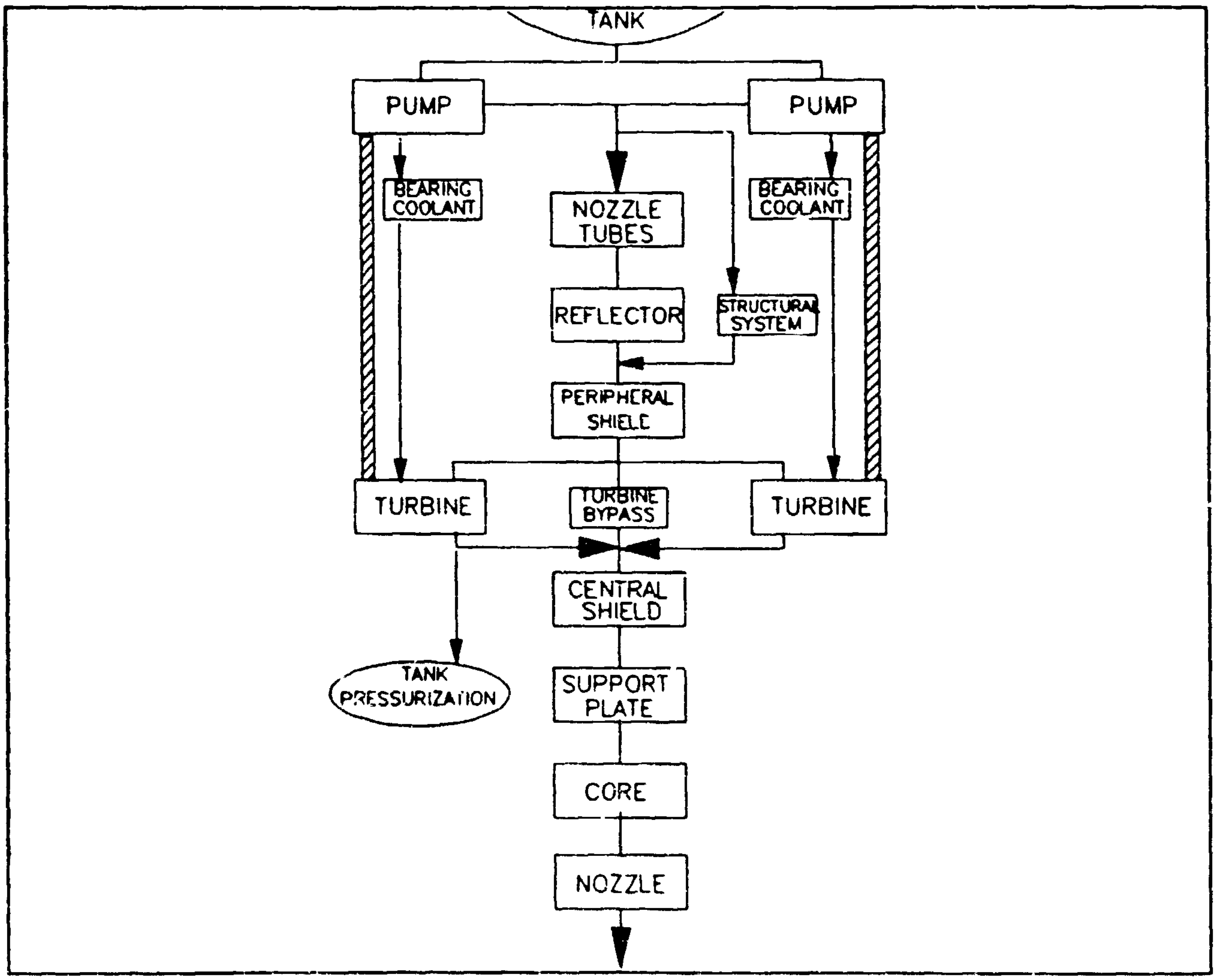

Figure 1. - Generic nuclear thermal propulsion system.

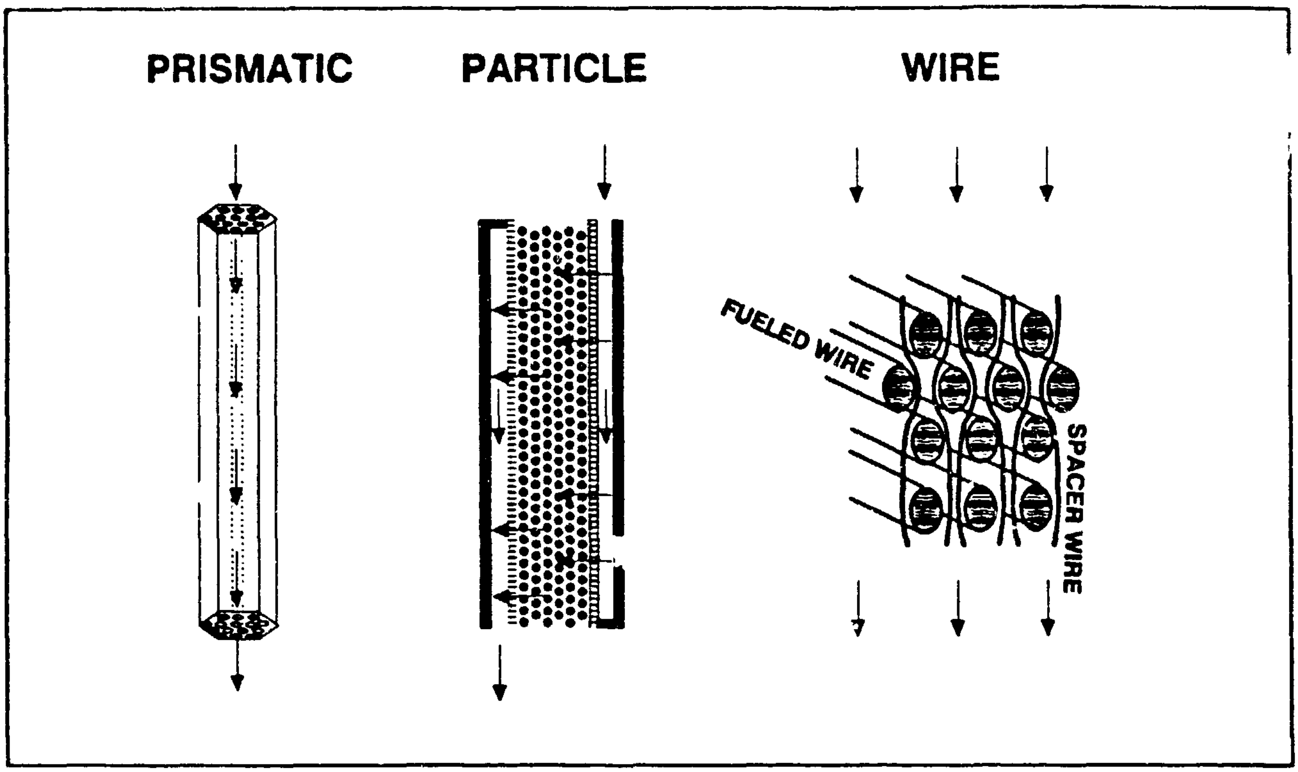

Figure 2. - Leading fuel forms.

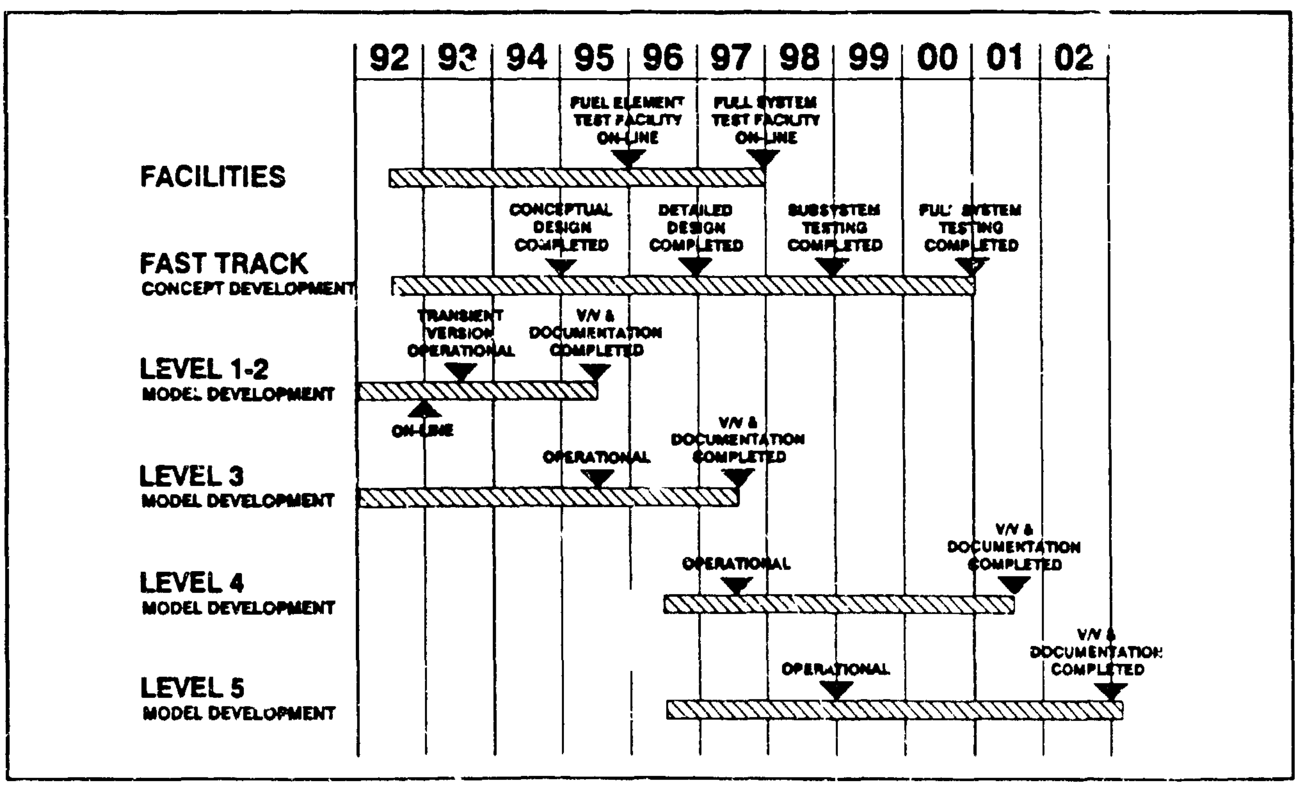

Figure 3. - Model development schedule.

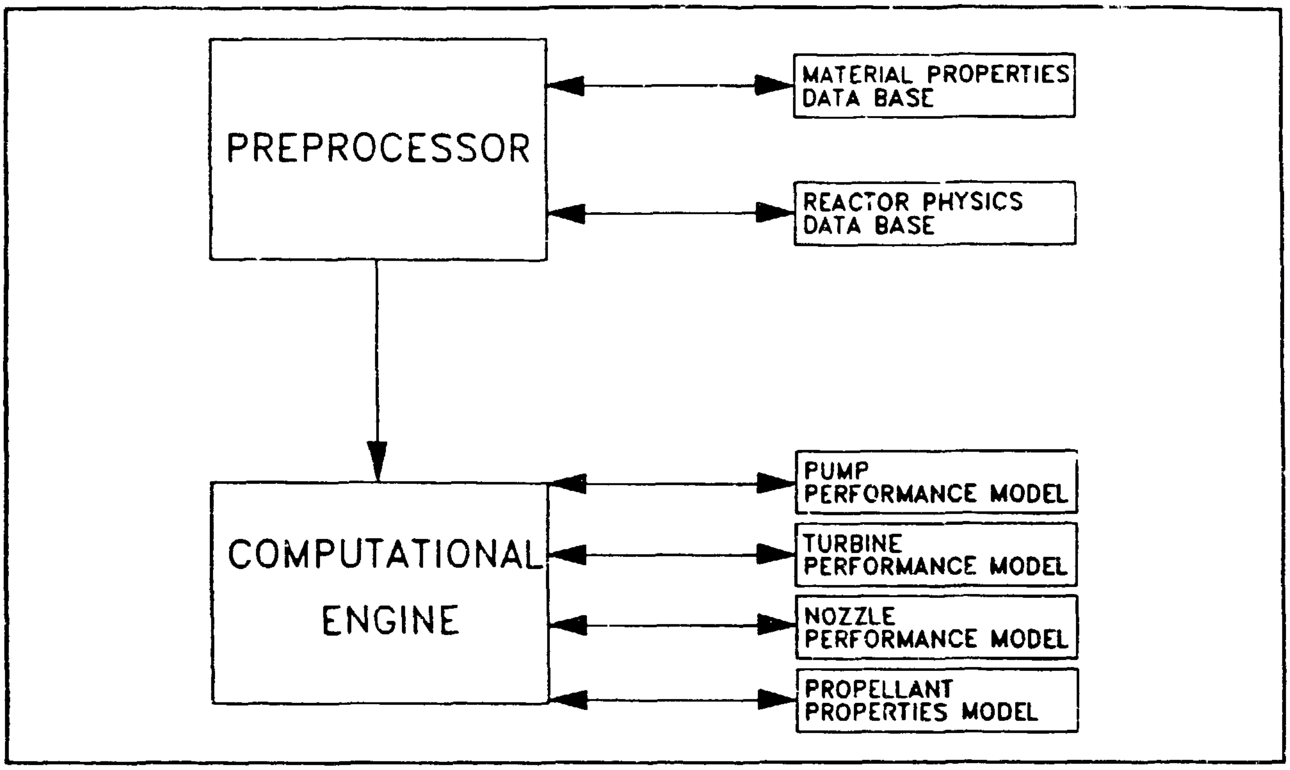

Figure 4. - Level 1 Model Structure.

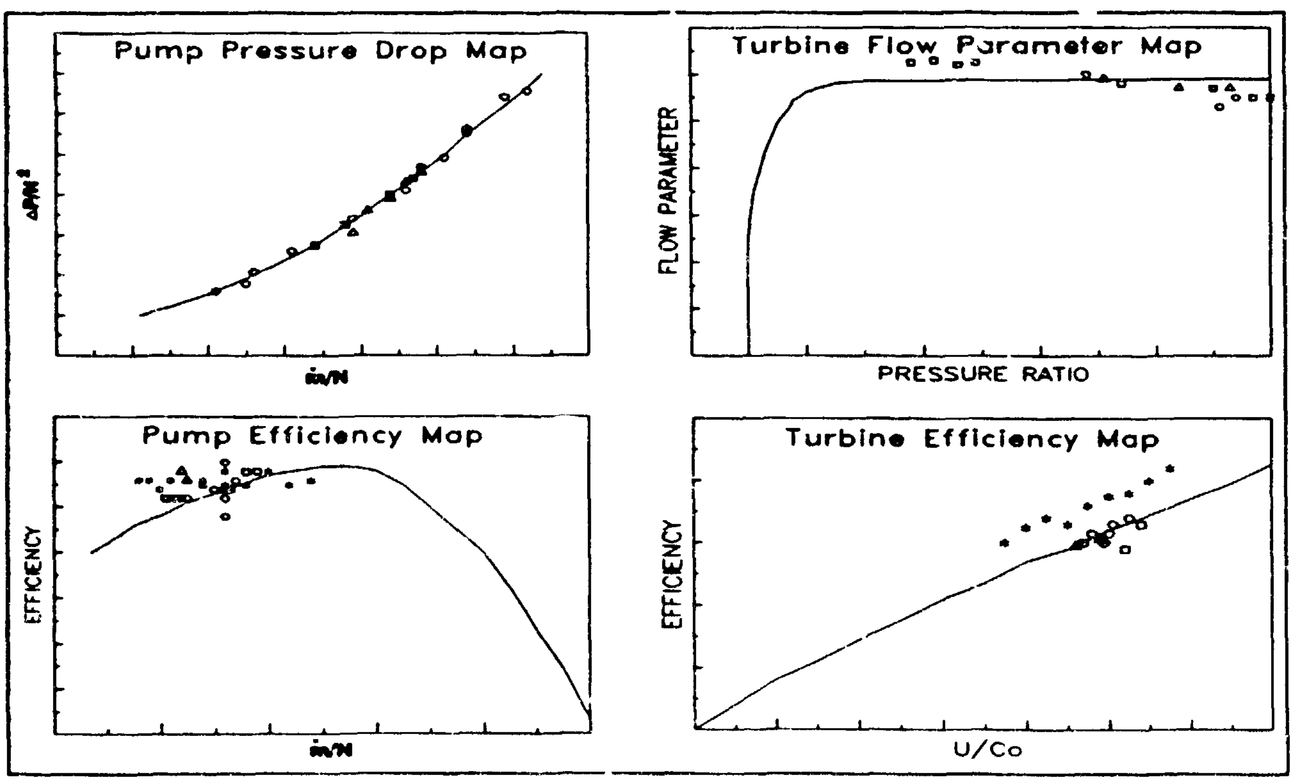

Figure 5 - Pump & Turbine Performance Maps.

REFERENCES

1. Report of the 90-Day Study on Human Exploration of the Moon and Mars. NASA TM-102999, 1989.

2. America's Space Exploration Initiative: America at the Threshold. The Report of the Stafford Committee to the President of the United States, May 1991.

3. Report of the Advisory Committee on the Future of the U.S Space Program. GPO, Washington D.C., 1990.

4. Walton, James T.: An Overview of Tested and Analyzed NTP Concepts. NASA TM-105252, September 1991.

5. Thornton, G.; and Rothstein, A.J.: Comprehensive Technical Report of the General Electric Direct-Air-Cycle Aircraft Nuclear Propulsion Program. General Electric Report APEX-901, June 1962.

6. Anon.: Nuclear Rocket Program Terminal Report. Argonne National Laboratory, ANL-7236, June 1966.

7 Pelaccio, D. G.; and Scheil Christine M.: Nuclear Thermal Propulsion Engine System Design Analysis Code Development. Presented at the 9th Symposium on Space Nuclear Power Systems, January 1992.

8 Anon.: N.E.T.A.P. (Nuclear Engine Transient Analysis Program) Program E31201. Aerojet Nuclear Systems Company, TID/SNA-957, February 1971.

9 Anon.: Nuclear Engine Transient Analysis Program. Aerojet General Corporation Report RN-DR-0068, October 1965.

10. Miller, J.: Common Analog Model Derivation (Power Range). Aerojet General Corporation Report 100-72-6 (TID-26044), May 1972.

11. Dryden, R.M.: NERVA Startup Common Analog Model - Equation Derivations. Aerojet General Corporation Report 100-72-2, June 1972.

12. Dobranich, Dean: SAFSIM: A Computer Program For Engineering Simulation of Space Reactor System Performance. Presented to the ANS Meeting for Nuclear Technology for Space Exploration, August 16-19, 1992.

13. Walton, J.T.: Program ELM. LEW-15423, available through COSMIC, University of Athens, Athens, Georgia, (404) 542-3265, 1991.

14. MacFarland, R.E.; and Muir, D.W.: NJOY Nuclear Data Processing System. LA-9303-M, 1985.

15. Briesmeister, J.F.: MCNP - A General Monte Carlo Code For Neutron and Photon Transport. LA-7396-M, September 1986.

16. Nickerson, G.R.; Berker, D.R.; Coats, D.E.; and Dunn, S.S.: Improvements to the Two-Dimensional Rocket Nozzle Performance Computer Program. Presented at the Ninth Symposium for Space Nuclear Power, January 1991.

17. Robinson, C.P.; Bartlit, J.R.; Stokes, R.W.; Conant, J.W.; and Edeskuty, F.J.: Conversion of Para to Orthohydrogen in Nuclear Rocket Radiation Fields. Progress in Refrigeration Science & Technology, Proceedings of the XIII International Congress of Refrigeration, Vol. 1, pp. 577-580, 1973.

18. McCarty, R.D.; Hord, J.; and Roder, H.M.: Selected Properties of Hydrogen (Engineering Design Data). U.S. Department of Commerce, National Bureau of Standards, Monograph 168, February 1981.

19. Walton, J.T.: NBS Parahydrogen Properties Data Base Program (NBS-pH2). Available through COSMIC as LEW-15505, 1992.

20. Anon.: NRX/EST Reactor Test Analysis Report. WANL-TNR-216, 1966.

21. Anon.: XE-Prime Engine Final Report. AGC RN-S-0510, 1970.